ground cannot be accurately converted to a rainfall rate on the path, and 2) the rainfall-rate model giving the drop-size distribution is not accurate enough to calculate the attentuation on the path.

In the radar-based diversity experiments, an S-band radar was used to accumulate detailed reflectivity measurements of the space surrounding the radar during rain events. These data were then used to calculate the rain attenuation along hypothetical Earth-space paths through the rain volume by applying the observed relation between reflectivity and attenuation. Diversity results were obtained by hypothesizing parallel paths, with their endpoints separated by a given distance. Results from a large number of different path pairs and a number of rain events were used to derive attenuation statistics and diversity gain. Because this method does not actually require a pair of diversity terminals, it is simple to vary the terminal spacing and baseline orientation.

#### 7.4.2.1.2 Site Diversity Design Factors

7.4.2.1.2.1 Separation Distance. Diversity gain depends strongly upon the earth terminal separation distance, d. The diversity gain increases rapidly as d is increased over a small separation distance, i.e., up to about 10 km; thereafter the gain increases more slowly until a maximum value is reached, usually between about 10 and 30 km. This maximum value is generally quite close to that value associated with uncorrelated fading at the individual earth terminals. Radar-based results, showing the variation of diversity gain with separation, are given in Figure 7.4-4.

In contrast to the uncorrelated case, one may argue that correlated fading may occur for paths separated by distances associated with typical rain cell separation distances. Such an effect may be inferred from the rainfall statistics of Freeny and Gabbe (1969); however, these statistics are associated with point rainfall rates rather than path average rainfall rates. No definitive report of this effect has been published to date.

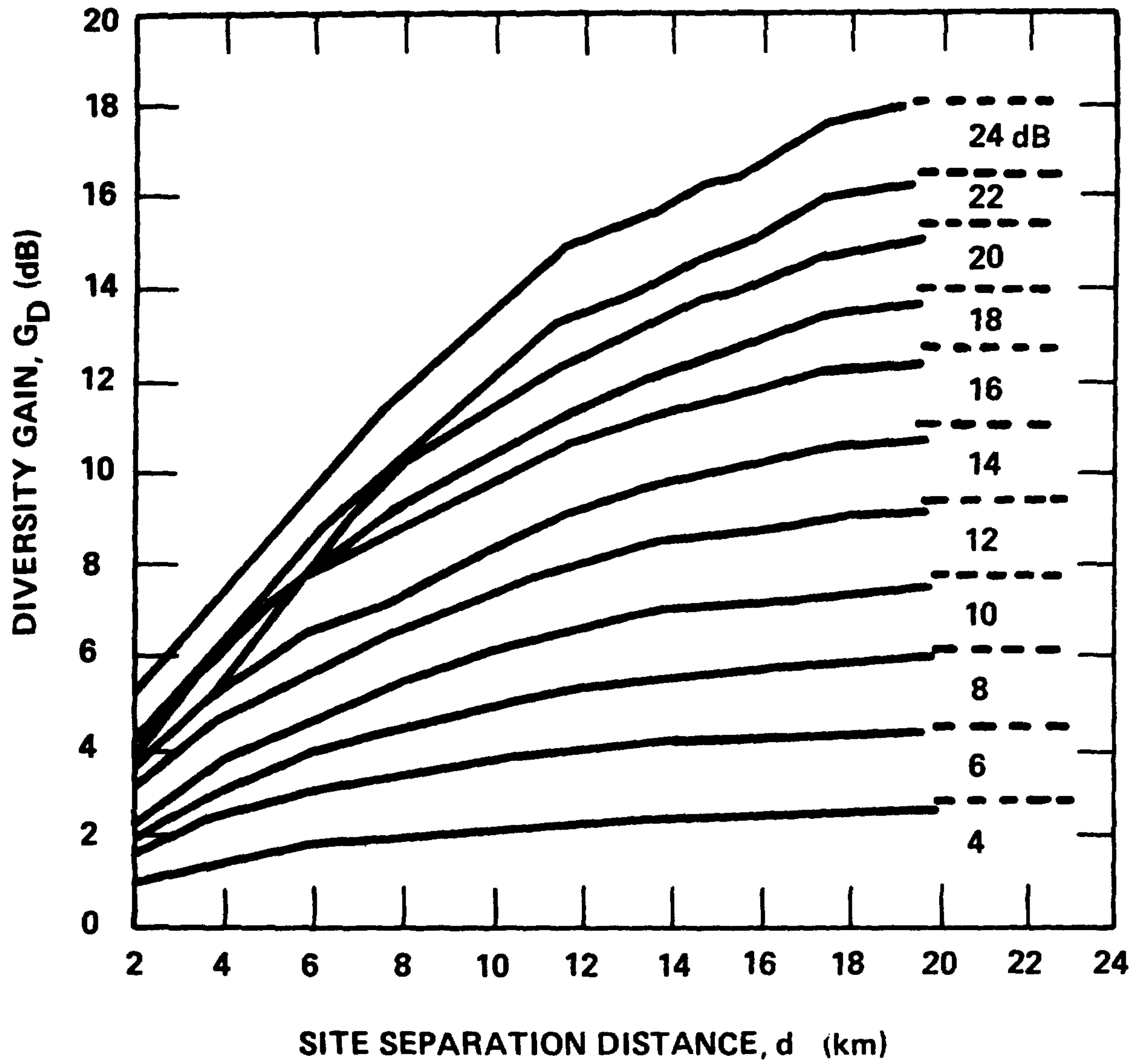


Figure 7.4-4. Diversity Gain, GD, versus Separation Distance, d, for 18 GHz. (Horizontal Dashed Lines Represent Optimum Levels) (Goldhirsh and Robison-1975)

7.4.2.1.2.2 Baseline Orientation. The perpendicular separation between parallel paths is greatest when the earth terminals are located on a baseline perpendicular to the projections of the paths on the earth's surface. This arrangement minimizes the possibility of both paths passing through the same rain cell. Nevertheless, the dependence of diversity gain on baseline orientation is quite weak except, possibly, for very short separation distances.

Mass (1979) has shown analytically for circular rain cells over two ground station sites alternately positioned transverse and parallel to the earth-space path, that only a small (0.3 to 0.4 db) difference in diversity gain is to be expected. It is anticipated that the orographic effects will overshadow these orientation effects.

The baseline orientation problem is further complicated if spatial anisotropy of the rain cells, i.e., a preferred direction of rain cell elongation, is known to exist in the region of interest. In this case, a baseline orientation perpendicular to the preferred axis of rain cell orientation would be desirable if the direction of the propagation path were ignored.

Considering both factors together, it appears that the most desirable baseline orientation is that which bisects the larger of the two angles between the projection of the propagation path and the preferred axis of rain cell orientation.

7.4.2.1.2.3 Path Elevation Angle. The separation distance required to achieve a given level of diversity gain increases as the path elevation angle decreases (Hodge-1978). This is due to the increased likelihood of path intersections with rain cells at lower elevation angles. This effect is coupled to the problem of rain cell anisotropy and path azimuth as noted below. Stated differently, the diversity gain decreases with decreasing elevation angle (Allnutt-1978).

7.4.2.1.2.4 Path Azimuth Angle. For synchronous satellites the path azimuth and elevation angles are not independent, and, thus, the dependence of diversity performance on these variables cannot be fully separated. If all rain cells were isotropic, one would expect no variation in diversity performance with azimuth angle other than that associated with the elevation angles. However, when rain cell anisotropy is considered, there appears to be a weak improvement in diversity performance for path azimuths in the southerly compass quadrant (in the northern hemisphere) that do not contain the preferred axis of rain cell orientation.

7.4.2.1.2.5 Link Frequency. Experimental measurements to date have shown a slight inverse dependency of site diversity gain on the link frequency for a given single-site attenuation over the 10-35 GHz frequency range (Hodge-1982). For link frequencies above 30 GHz, attenuation on both paths simultaneously due to uniform rain systems can be significant. This results in an apparent frequency threshold to the diversity gain (Kaul-1980) and will be discussed later.

7.4.2.1.2.6 Anisotropy of Rain Cells Along a Front. There is a tendency for convective rain cells associated with frontal activity to occur in bands nearly perpendicular to the direction of movement of the front. The direction of motion of the cells within such a band tends to be along or slightly ahead of the direction of the front. Furthermore, the more intense cells tend to elongate in their direction of motion (Harrold and Austin-1974). Thus, two types of anisotropy are evident. The first is associated with the elongation of individual cells and is related to the probability of parallel paths passing through the same cells. The second is associated with the statistics of the vector separation between rain cells and is associated with the probability of parallel paths simultaneously intersecting two different rain cells. Fortunately, these two preferred orientations are nearly parallel, and thus the same corrective action is required in each case. Namely, the baseline orientation should be nearly perpendicular to these preferred directions.

7.4.2.1.2.7 Local Climatology. To a first order of approximation it is commonly assumed that the probabilities of rain cell occurrence are uniformly distributed over rather large regions of the earth's surface. This assumption may be invalidated by the presence of any one of the following features:. mountains, large valleys, large bodies of water, or urban heat "islands". These features can give rise to nonuniform spatial distributions of rain cell probabilities.

Spatial distributions of rainfall accumulation are readily available in the meteorological literature; however, it is not currently known whether the use of these data is applicable to the question of earth terminal siting. For example, it may be argued that these rainfall accumulations are dominated by low rainfall rates and thus do not reflect the spatial distributions of intense rain cells that produce high attenuation levels on earth-space paths.

7.4.2.1.2.8 Switching Rates. The rate of change of attenuation on a single path is relatively slow. The highest rates reported are on the order of 0.6 dB/S at 11.8 GHz (Dintelmann, 1981) and 0.4 dB/S at 11.7 GHz (Nakoney, 1979), as reported in CCIR Report 564-3, Annex I (CCIR-1986). This implies that the decision and switching process for diversity paths may be quite slow and should pose no significant problem in the system design.

7.4.2.1.2.9 Connecting Link. The implementation of a path diversity system must incorporate a connecting link between the two earth terminals. If this link is closed, i.e., waveguide, coax, etc., its performance will be independent of meteorological variables and will not directly influence the reliability improvement provided by the use of path diversity. If, however, the connecting link operates above 10 GHz in the atmosphere, the joint fading statistics of the connecting link with the earth-space paths must be considered. This degrading effect appears to be small except for cases of very long baselines or baseline orientations parallel to the earth-space propagation paths (Ferguson and Rogers-1978).

7.4.2.1.2.10 Multiple Earth Terminals. Substantial link reliability improvements result from the use of two earth-space propagation paths. Thus one may conjecture that further improvement might result from the addition of additional diversity paths. Determination of diversity gain for N diversity terminals shows that most of the gain is realized for two terminals with very little further increase in gain for additional terminals (Hodge-1974b).

7.4.2.1.3 Empirical Model for Site Diversity Gain

7.4.2.1.3.1 Description of the Model. The data available from early diversity experiments in New Jersey and Ohio (Hodge-1974a, Wilson-1970, Wilson and Mammel-1973, Gray-1973) were used to develop an empirical model for the dependence of diversity gain on separation distance, d, and single site attenuation, A (Hodge-1976a). The resulting model is of the form

$$G_D = a'(1-e^{-b'd}) \qquad (7.4\text{-}5)$$

where the coefficients a' and b' depend upon the single site attenuation according to

$$a' = A - 3.6\ (1-e^{-0.24A}) \qquad (7.4\text{-}6)$$

$$b' = 0.46\ (1-e^{-0.26A}) \qquad (7.4\text{-}7)$$

The empirical diversity gain model has been improved (Hodge - 1982) to include other factors besides single-site attenuation and separation distance. Based on data from thirty-four diversity experiments, the improved model takes into account the following variables, listed in decreasing degree of dependence

| | |
|---|---|
| Separation distance | d |
| Single-site attenuation | A |
| Link frequency | f |

Elevation angle EL

Baseline-to-path angle $\Delta$

The variable $\Delta$ is the angle between the intersite baseline and the ground projection of the Earth-space propagation path, measured in such a way that $\Delta \leq 90°$. Using the definitions of Figure 7.4-2,

$$\Delta = |AZ - \beta| \tag{7.4-8}$$

The improved model also eliminates the implication of the earlier model that diversity gain approaches a constant (3.6 dB) for very deep fades. This has been found to be incorrect in more recent experiments.

The model gives the diversity gain as

$$G_D = G_d G_f G_E G_\Delta \tag{7.4-9}$$

where each factor contains the dependence of the variable denoted by its subscript. The first factor is the same as the gain of the earlier model:

$$G_d = a(1-e^{-bd}) \tag{7.4-10}$$

The regression coefficients are given by

$$a = 0.64A - 1.6\ (1 - e^{-0.11A}) \tag{7.4-11}$$

$$b = 0.585\ (1 - e^{-0.98A}) \tag{7.4-12}$$

The remaining factors are

$$G_f = 1.64\ e^{-0.025f} \tag{7.4-13}$$

$$G_E = 0.00492(EL) + 0.834 \tag{7.4-14}$$

$$G_\Delta = 0.00177\ \Delta + 0.887 \tag{7.4-15}$$

In these formulas, d is in kilometers, A is in decibels, f is in gigahertz, and EL and $\Delta$ are in degrees. Figure 7.4-5 gives graphs of a, b, $G_f$, $G_E$ and $G_\Delta$ to assist in application of the model.

The improved model predictions were compared with the original data set and produced an rms error of 0.73 dB. The data set used consisted of the results of thirty-four diversity experiments (including most of those listed in Table 7.4-1), covering a wide range of variable values.

Use of the empirical model is illustrated in Figure 7.4-6. It shows measured diversity gain as a function of average single-site attenuation for the VPI and SU SIRIO Diversity Experiment (Towner, et al - 1982). As indicated, the curve applies to one full year of data at 11.6 GHz. The figure also shows the predictions of the empirical model. The improved version of the model appears to give a better agreement with experimental measurements than the original version. However, the measured diversity gain falls well below that predicted for single site attenuation values above about 11 dB. The reason for this typical behavior is not known, but it could be attributed to the limited time period (one year), or to the especially low elevation angle (10.7°).

7.4.2.1.3.2 Extension of the Empirical Model. Kaul (1980) has introduced meteorological considerations to the original empirical model which establish practical limits on the diversity gain depending on A, f, EL and other system parameters.

The extended empirical model considers that diversity gain is only realized when spatially nonuniform rain rates occur near the ground station. (A ground system imbedded in a uniform rain experiences zero diversity gain.) Convective (thunderstorm) rains are assumed to represent these non-uniform rain systems. Rice and Holmberg (1973) described rain types analyically as Mode 1 (thunderstorm) and Mode 2 (stratiform) rains (see Section 3.2). Using the Rice and Holmberg model, the cumulative distributions of

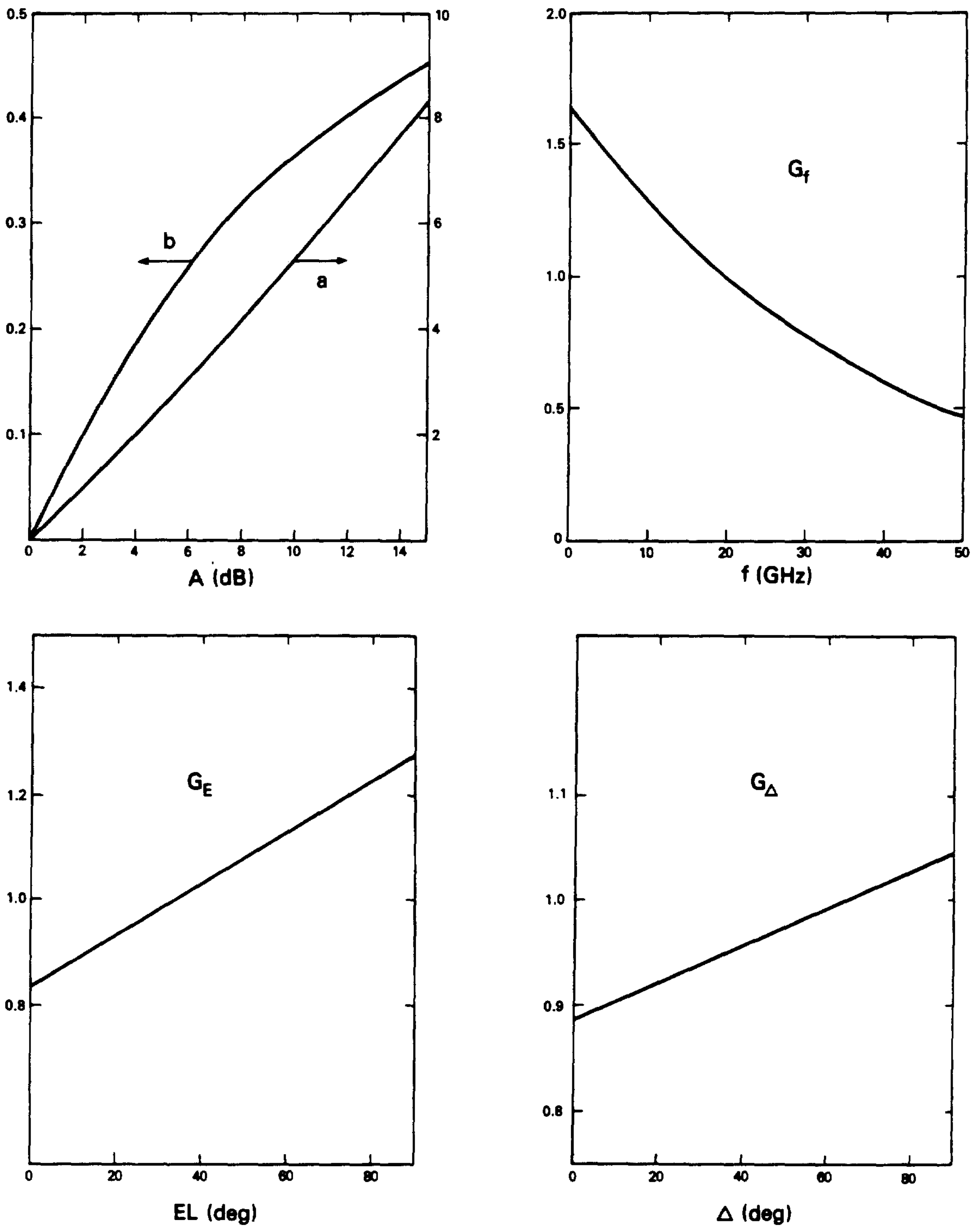


Figure 7.4-5. Parameters of Improved Diversity Model

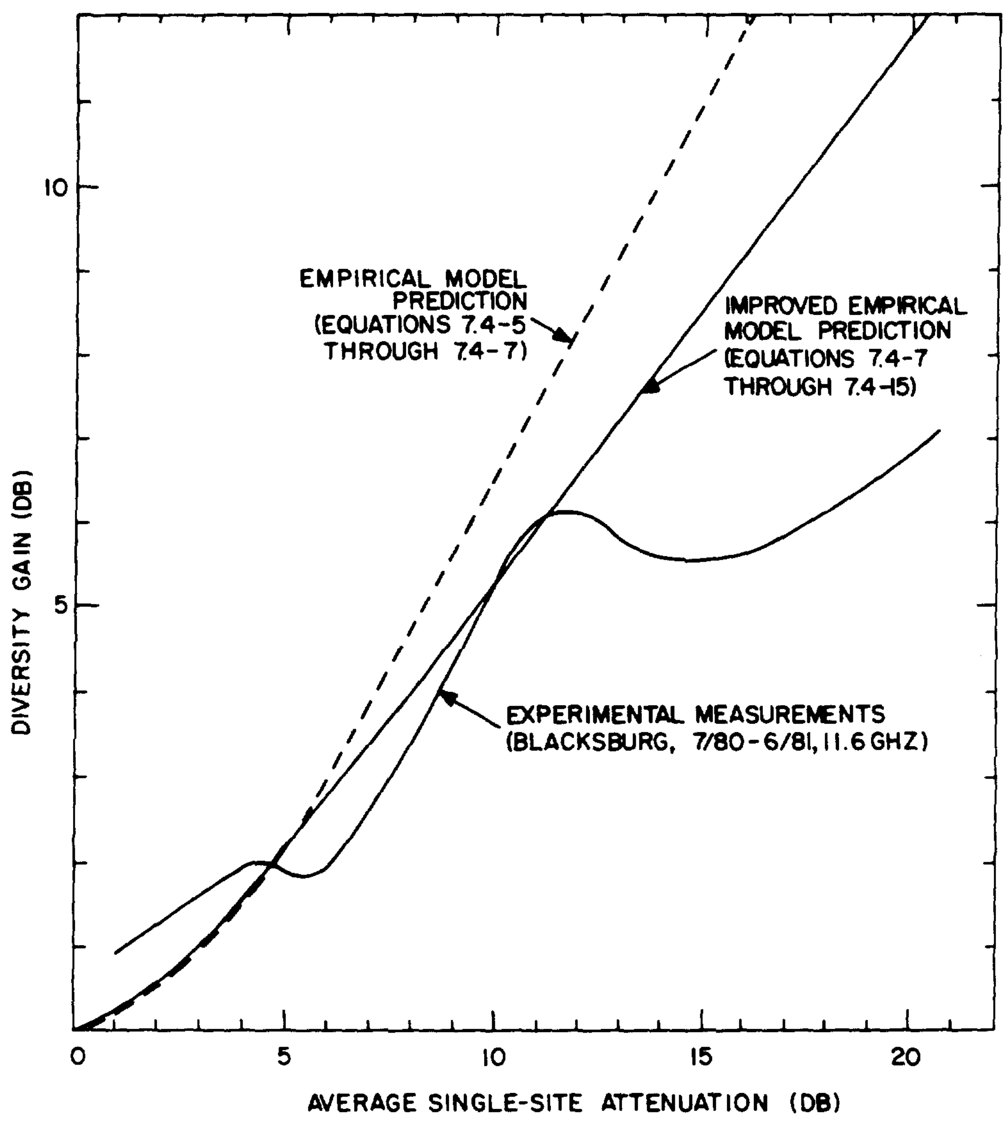


Figure 7.4-6. Comparison of Diversity Models and Experimental Results

total rain rate and uniform (Mode 2) rain rate may be developed as shown in Figure 7.4-7. Diversity gain will be obtained only for that portion of time between the stratiform and total rain curves. For $\beta = 0.3$ and $R < 10$ mm/h, this time is small (7.6 h/yr) and decreases (increases) as $\beta$ and M decrease (increase). Therefore diversity gain will be large in Florida ($M \simeq 1000$ mm and $\beta = 0.7$; $M\beta \simeq 700$ mm) but will be small in Los Angeles ($M \simeq 250$ mm and $\beta = 0.1$; $M\beta \simeq 25$ for a given percentage of time. It appears that the $M\beta$ product is a good measure of the available diversity gain.

The amount of diversity gain available is also a function (to first order) of frequency, elevation angle and other meteorological parameters (height of the zero degree isotherm, etc.) as described in the attenuation model of Crane (1980). The results for a 30 GHz earth-space signal to a 40 degree elevation angle station located at sea level are shown in Figure 7.4-8. The difference between the attenuation arising from all rain events and uniform (stratiform) events is the maximum gain available for a diversity system. The time has been normalized to the amount of time the rain rate exceeds 0.25 mm/h (0.01 inch/h) in a year (350h). This same threshold value was selected by Lin (1973).

The total diversity gain available (see Figure 7.4-8) is the difference between the attenuation associated with all rain events and the attenuation attributed to stratiform (uniform) rain events. The maximum diversity gain available for one additional earth station (total of two identical earth stations) is $G_1$ and is computed from the cumulative distribution determined by the relation (Hodge-1978)

$$P_{cn}(A) = \left\{P_c(A)\right\}^n \tag{7.4-16}$$

where:

n = the number of (identical) earth stations,

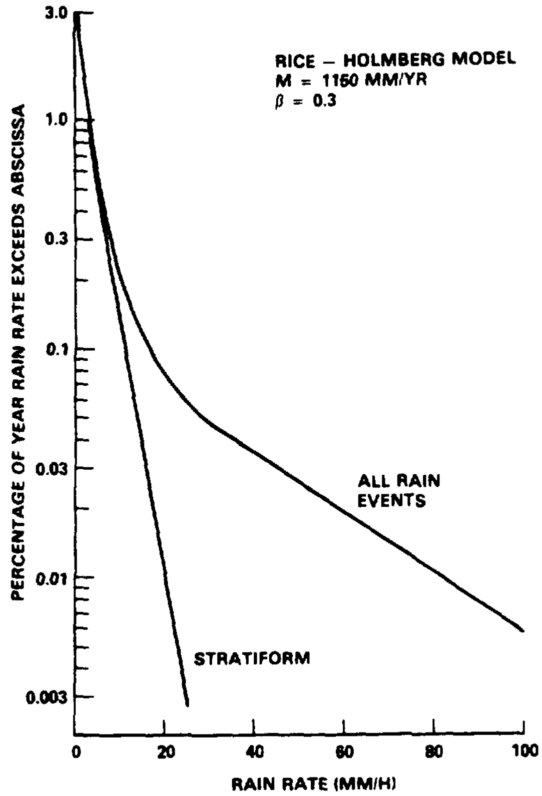


Figure 7.4-7. Cumulative Distribution of Rain Rate for Uniform and All Rain Events

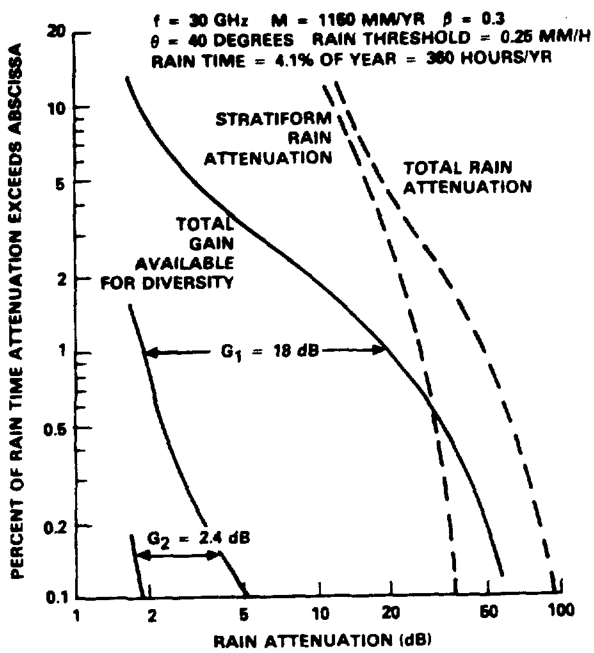


Figure 7.4-8. Cumulative Distribution of Total and Stratiform Rain Attenuation Plus Gain Available for Diversity Systems

$P_c(A)$ = the percent of time the attenuation A is exceeded for a single site, and

$P_{cn}(A)$ = the percent of time the attenuation A is exceeded for n identical sites.

$G_1$ and $G_2$ (the gain added by a third station) are shown in Figure 7.4-8. Plots of $G_1$ and $G_2$ versus the total attentuation on the worst path are given in Figure 7.4-9 for the region with M = 1150 and $\beta$ = 0.3. The corresponding plots for a region with $\beta$ = 0.7, such as Florida, are also given. Note the shift off zero which arises due to the effect of the uniform rains. For the case of $\beta$ = 0.7 the gain $G_1$ saturates. This saturation prevents unrealistic system gains from being estimated as shown earlier. The saturation effect is believed to exist whenever the Mode 1 rain term dominates, but this has not been proven.

The maximum diversity gain $G_1$ for a two-station diversity system at selected frequencies is shown in Figure 7.4-10. Here the effects of stratiform rain at higher frequencies are clearly evident. For example at 45 GHz the zero diversity gain intercept occurs near 40 dB attenuation which will be observed about 0.4% (35 hours) of each year. Therefore for 45 GHz system links which can accommodate outages in excess of 35 hours per year, a diversity system will reduce the outage time or reduce the link margin required for 0.4% availability by only a small amount.

Based on the experimental results (Goldhirsh- 1979) and the analytic results (Morita and Higuti- 1978 and Wallace - 1981) the term $G_1$ may be related to the empirical a' multiplier by the approximate relation

$$a' \simeq 0.9 \, G_{D1} \qquad (7.4\text{-}17)$$

Also the station separation dependence may be retained as before so that

$$G = 0.9 \, G_1(1 - e^{-b''d}) \qquad (7.4\text{-}18)$$

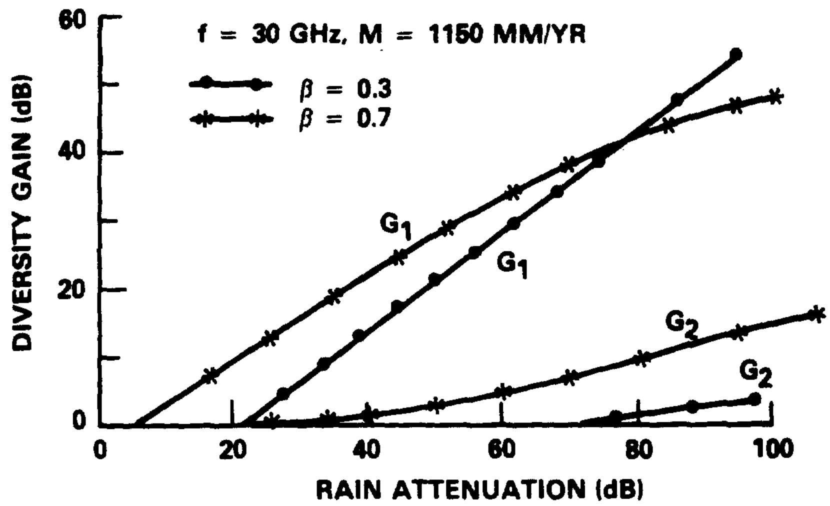


Figure 7.4-9. Maximum Diversity Gains G1 (Two Stations) and G2 (Three Stations) Versus Single-Site Attenuation

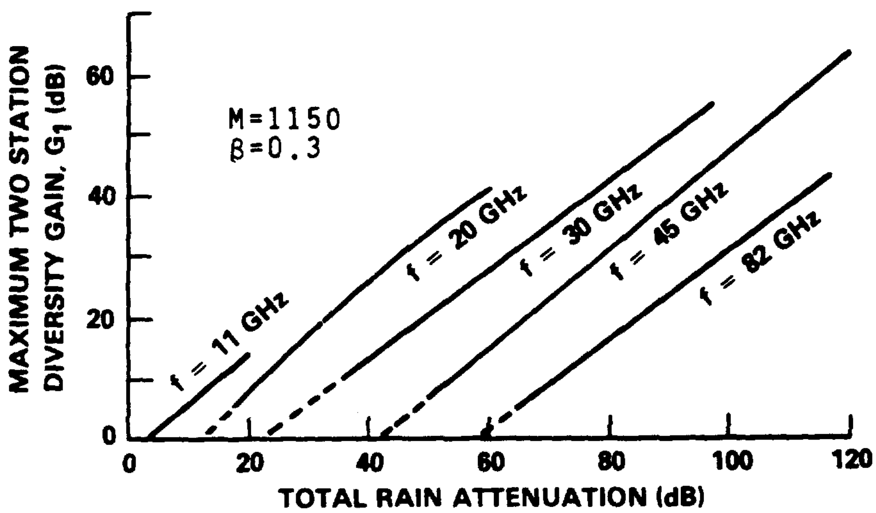


Figure 7.4-10. Maximum Diversity Gain, G1 Versus Attenuation for Selected Frequencies

except that

$$b'' = 0.46\ (1 - e^{-0.24(A-Ai)}),\ A>A_i \qquad (7.4\text{-}19)$$

which accounts for the frequency dependent intercept attenuation Ai as shown in Figure 7.4-10.

The observation that diversity gain is obtained only for nonuniform rains has been used to devise a very simple approximation to diversity gain versus single-site attenuation (Allnutt & Rogers - 1982). As shown in Figure 7.4-11, the relation is assumed to be approximated by two straight line segments. One line is parallel to the "ideal diversity gain" curve (diversity gain = attenuation). The second line joins the origin and the first line at a point called the "knee." The single-site attenuations at the "knee" and the "offset" determines the relation for a particular location, frequency, and elevation angle. Site spacing and baseline orientation are assumed to be such that, to first order, site separation effects are removed. The value of the "offset" attenuation is the single-site attenuation exceeded for 0.3% of the time, which is assumed to correspond to uniform rainfall. The "knee" attenuation is the single-site attenuation corresponding to a 25 mm/hr rain rate, considered to be the breakpoint between stratiform and convective rain. This simple model provided a good fit to one year of radiometric measurements obtained in West Virginia, at 11.6 GHz. However, the fit to data from Austria and Florida was poor. A subsequent refinement to the model (Allnutt & Rogers-1983) utilized the CCIR rain attenuation model as modified by CCIR Interim Working Party 5/2 in May 1982. These predictions were much more consistent, and a clear trend of increasing diversity performance with elevation angle and rain convectivity was established.

7.4.2.1.4 An Analytical Diversity Model

An alternate model of site diversity has been proposed (Wallace-1981) that is derived from analytical representations of the joint

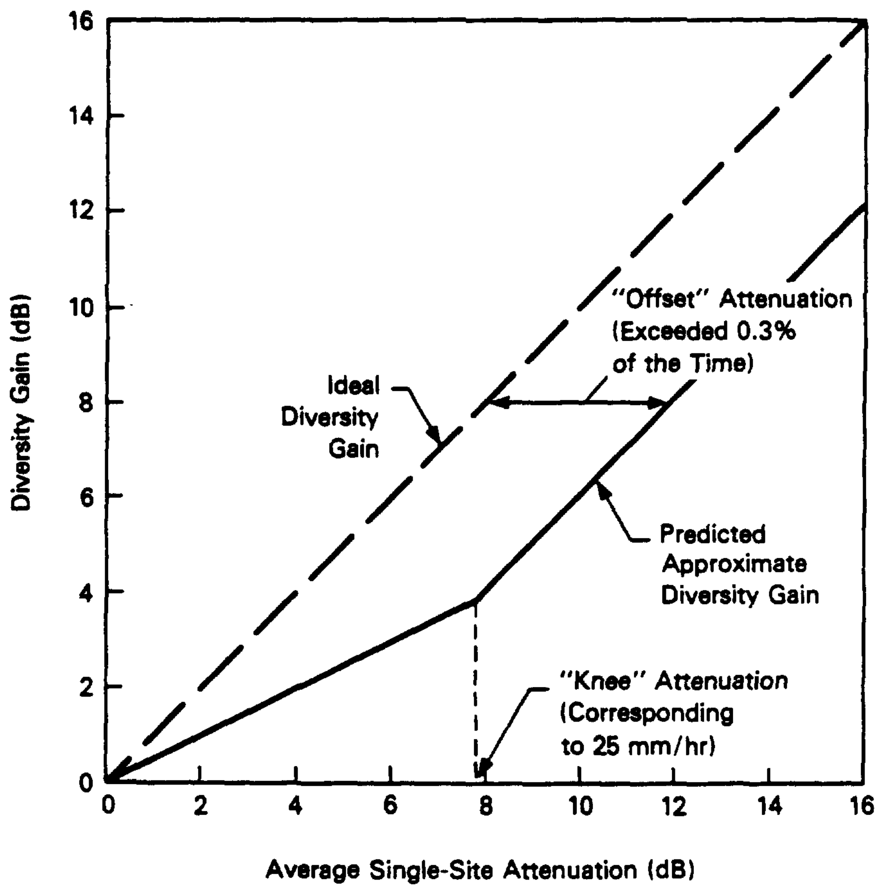


Figure 7.4-11. Construction of Approximation to Diversity Gain Prediction

site rain attenuation statistics. It is based on the well-known observation (Lin-1973) that rain attenuation in decibels, conditioned on the presence of rain, is approximately log-normally distributed. This is expressed analytically by the following:

$$\text{Prob}\ (A<a) = F_A(a) = P_o K \Phi(Z, m, \sigma) \qquad (7.4\text{-}20)$$

where

A = attenuation in decibels, a random variable

a = a particular value of A

$F_A(a)$ = cumulative distribution function (CDF) of A

$P_o$ = probability of rain

K = $\log_{10} e$, a scaling factor

$$\Phi(z,m,\sigma) = \frac{1}{\sqrt{2\pi}\,\sigma} \int_0^Z \exp\left[-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2\right] dx \qquad (7.4\text{-}21)$$

m = mean of log A

$\sigma$ = variance of log A

The "exceedance probability" or "time percentage of exceedance" customarily used as the abscissa in presenting attenuation or rain rate statistics is the inverse, or one minus, the CDF (see Section 6.3.1.1). The factor $P_o$ expresses conditioning on the presence of rain mentioned above. This conditioning effectively reduces the time during which the log-normal distribution applies to the fraction of time that it is raining. The parameter m is the same as the logarithm of the median attenuation during the time it is raining, or the value that is exceeded for half the raining time. $\sigma$ is a measure of variability of the attenuation. It is large if the attenuation is much greater or much less than the median value for significant periods of time. Typical values of median attenuation, or $10^m$ , lie in the 0.3 to 0.5 dB range for 16 GHz links (Lin-1973), and understandably increase with frequency. $\sigma$ is typically 0.5 to 0.8 and is highly dependent on the nature of the rain in a given location.

Given a log-normal estimate of the rain attenuation at a single ground station, it is a natural step to hypothesize that the attenuation experienced on links to two diversity sites is approximately jointly log-normal. This means that the logarithm of the attenuations at the two sites have a joint CDF that is bivariate Gaussian. The attenuation values are probabilistically related by a correlation coefficient, r, that varies with the site spacing. When the sites are distant from each other, we can say that their respective rain attenuations are uncorrelated, which corresponds to $r = 0$. The correlation coefficient increases to a maximum of one as the sites become closer together. One would intuitively expect the diversity gain achieved with two sites to be an inverse function of this correlation coefficient.

The effective amount of rain attenuation experienced by a diversity pair of earth stations is just the minimum of the values of attenuation seen at each site, since ideally one would always be using the site that has the least. Applying this fact, the CDF of the diversity pair rain attenuation can be determined from the joint CDF of the attenuation of the individual sites. This was done by Morita and Higuti (1978) using the joint log-normal hypothesis. The resulting CDF is also approximately log-normal, but with parameters m and $\sigma$ both less than the corresponding parameters for either site. By comparing the single-site attenuation CDF with the diversity pair attenuation CDF, the diversity gain can be found. This has been done for a range of parameter values, and the results are shown in Figure 7.4-12. The axes in this figure are normalized by dividing the variables by the median single-site attenuation value, $10^m$. A significant observation made from the figure is the insensitivity of diversity gain on the value of $\sigma$, except for very low values of r.

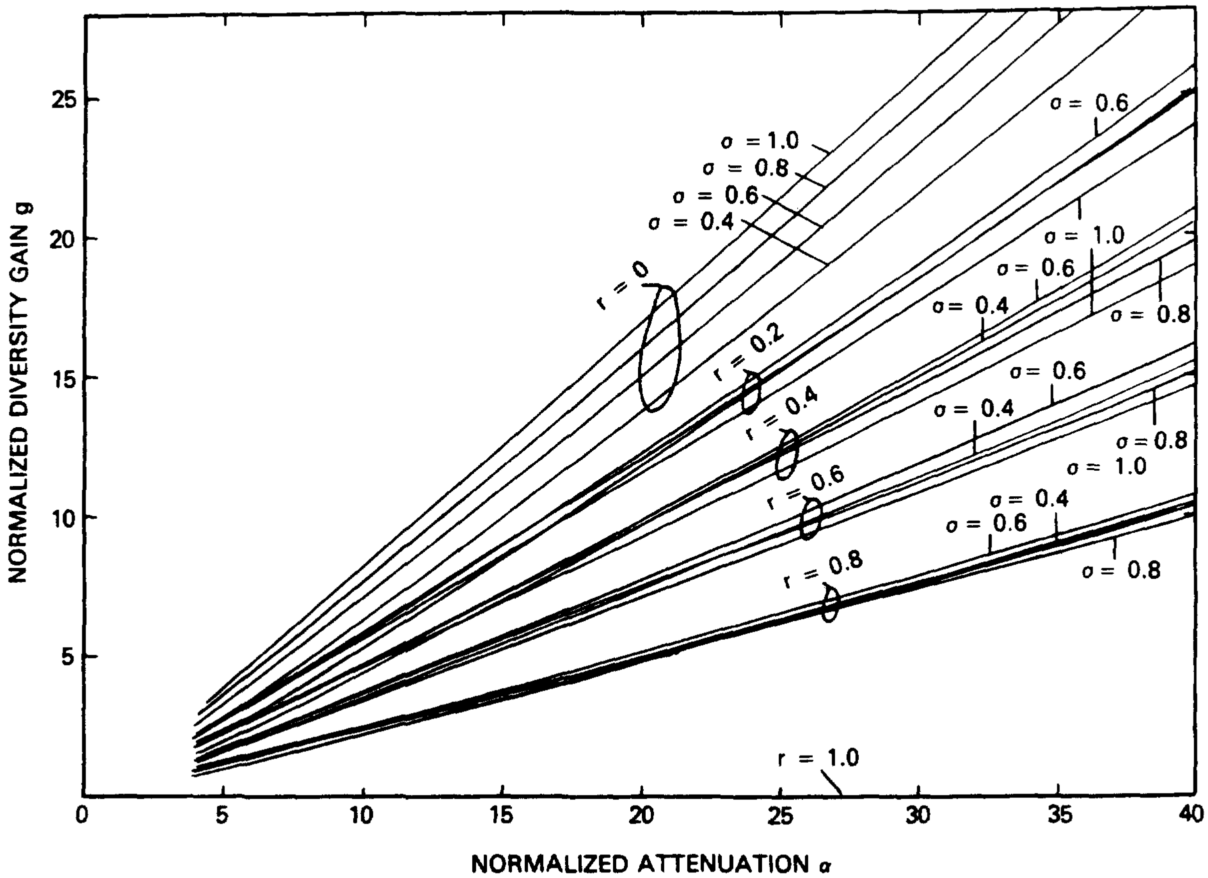


Figure 7.4-12. Diversity Gain Versus Attenuation for Varying Distribution Parameters (Normalization is with Respect to Median Attenuation)

A drawback of this analytical model is that it requires values of parameters that are not normally computed in current experiment data analysis. Specifically, the median value of attenuation, conditioned on the presence of rain, is usually unknown, as is the correlation coefficient. Morita and Higuti (1978) computed a theoretical correlation coefficient as a function of site separation that is consistent with Japanese experimental results. However, there is some evidence suggesting that the Japanese correlation model does not apply as well to U.S. data (Wallace-1981). It is likely that the correlation coefficient is highly dependent on other factors besides site separation, such as local "microclimate" variations and orographic effects (Allnutt-1978).

#### 7.4.2.1.5 Relative Diversity Gain

Based on radar-derived diversity gain data, Goldhirsh (1975) observed that the frequency dependence of site diversity gain can be eliminated by introducing a new parameter: relative diversity gain. Relative diversity gain $G_r$ (d)for any particular site spacing d is equal to the measured diversity gain at spacing d and frequency f divided by the maximum diversity gain achievable at that frequency:

$$G_r(d) = G_d(d, f)/\mathrm{Max}[G_d(d, f)] \tag{7.4-22}$$

The maximum achievable diversity gain, assumed to be that corresponding to statistically independent rain attenuation at the two diversity sites, is not precisely defined. For any particular single-site attenuation value, the diversity gain approaches an asymptotic value as separation distance is increased, but it is often difficult to say what that value is. Goldhirsh assumed that 35 or 40 km was the distance giving the maximum diversity gain for purposes of defining $G_r$.

An analytical best-fit to the relative diversity gain versus site separation curve was found by Goldhirsh (1982) to be as follows:

$$G_r(d) = 1 - 1.206 \exp(-0.53 \sqrt{d}) \tag{7.4-23}$$

The difference between radar-derived $G_r$ values and this function was less than 5% over the d = 1 to 30 km range.

### 7.4.2.2 Orbit Diversity

As already discussed, orbit diversity refers to the use of two satellites at separate orbital positions, which provide two paths to a single ground terminal (Ippolito-1986). Orbit diversity is generally less effective than site diversity for rain fade mitigation because the diversity paths are more highly correlated. Nevertheless, orbit diversity has the advantage that the two satellites can be shared (as part of a resource-sharing scheme) with many ground sites. This is in contrast to the case of site diversity, where the redundant ground site can generally be dedicated to only one primary ground site (Matricciani-1987). Therefore, site diversity is somewhat inefficient in the sense that the redundant ground site is not used most of the time. On the other hand, if an orbit diversity scheme does not take advantage of its capability for resource-sharing with several ground sites it, too, is inefficient and is likely to prove too expensive for the amount of diversity gain that it does provide.

Of course, operational considerations other than rain fades can also make the use of orbit diversity more attractive. Examples of such operational considerations include satellite equipment failures, and sun transit by the primary satellite, both of which require handover to a redundant satellite to maintain communication. So the use of a redundant satellite for other reasons in addition to rain fades can help to make orbit diversity economically practical.

If a ground terminal is to take full advantage of orbit diversity, it really should have two antenna systems, so that the switching time between propagation paths can be minimized. If the terminal has only one antenna system with a relatively narrow beamwidth, switching time can be excessive because of the finite time required to slew the ground antenna from one satellite to another, and because of the finite time needed for the receivers to re-acquire the uplink and downlink signals. Of course, the use of two spatially separated ground antennas provides an opportunity for site diversity in addition to orbit diversity.

Satellites in geostationary orbit are desirable for orbit diversity because they appear to the ground station to be fixed in space. Such orbits simplify satellite acquisition and tracking, and alleviate satellite handover problems. However, satellite coverage of high northern and southern latitudes is limited - requiring ground antennas at these latitudes to operate at low elevation angles. In addition, rain attenuation is greater at low elevation angles because of the longer path lengths through rain cells. To overcome this difficulty with high-latitude stations, elliptical orbits whose apogees occur at high latitudes can be used, allowing satellite coverage for a relatively large fraction of the orbit period. However, not only are the advantages of geostationary orbits then lost, but in addition several satellites must be used in order to provide coverage at all times.

Although data concerning the improvement achievable with orbit diversity are currently rather sparse, recent predictions of the achievable improvement have been made (Matricciani-1987). One configuration that thas been analyzed consists of:

1. A ground station at Spino d'Adda in Northern Italy

2. Satellite 1 (Italsat) at 13 deg. E longitude

3. Satellite 2 (Olympus) at 19 deg. W longitude.

For a 20 GHz downlink, the predicted single-path and double-path statistics are shown in Figure 7.4-13. The diversity (double path) predictions shown in this figure assume that Satellite 1 is normally used, and that Satellite 2 is switched in only when the rain attenuation for Satellite 1 exceeds some selected value. Because Satellite 2 would therefore be used only a small fraction of the time, it can be time shared with several ground stations for large-scale orbit diversity. The predictions are based on single-path measurements of the rain-rate probability distribution, and the joint distribution for the double-path attenuation is assumed to be log-normal.

Measurements of orbit diversity improvement have been made (Lin, et al-1980) for a configuration consisting of:

1. A ground station at Palmetto, GA

2. Path 1 - 18 GHz radiometer pointed in direction of COMSTAR D1 at 128 deg. W longitude

3. Path 2 - 19 GHz beacon of COMSTAR D2 at 95 deg. W longitude.

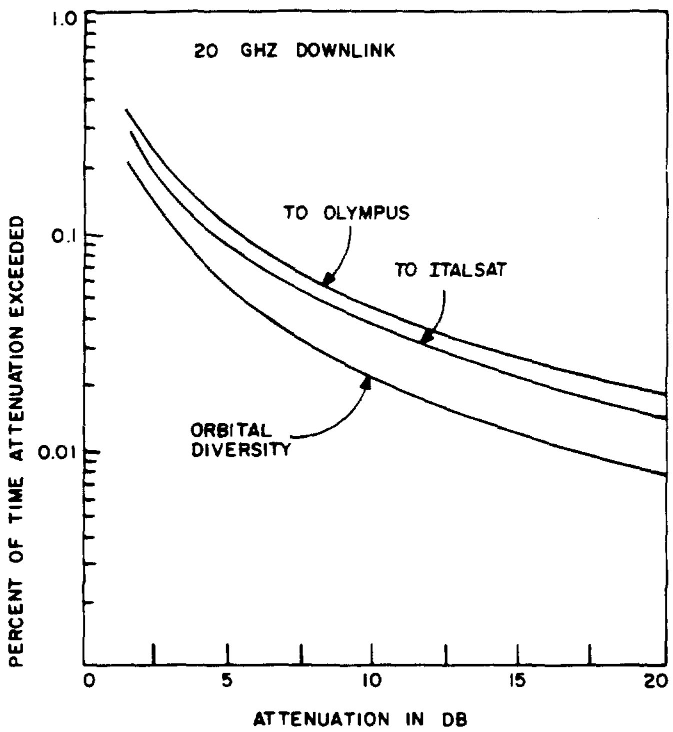


Figure 7.4-13. Predicted Orbit Diversity Performance at Spino d'Adda, Italy

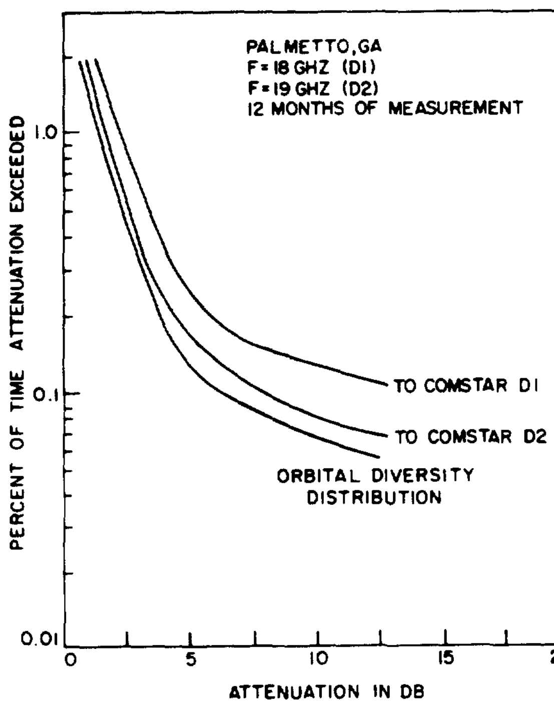


Figure 7.4-14. Orbital diversity measurements at Palmetto, GA

Figure 7.4-14 shows measurement results at 18 and 19 GHZ. One might expect the diversity gain to improve markedly as the angle subtended increases. However, it turns out (Ippolito-1986) that except when the single-path attenuation is large to begin with, the diversity gain actually increases rather slowly with the subtended angle. This is because most of the rain attenuation is at low altitudes, so that even widely diverging propagation paths often pass through the same rain cell.

Of course, the measurements in Figure 7.4-14 cannot be directly compared with the predictions in Figure 7.4-13 because the rain statistics and geometrical configurations differ. Nevertheless, the limited measurements and calculations that have been made both indicate that a modest diversity gain is achievable from orbit diversity. In any case, orbit diversity gain is less than that achievable with site diversity. Figure 7.4-6, for example, shows that one can expect roughly five dB site diversity gain when the average single-site rain attenuation is 10 dB. Figures 7.4-13 and 7.4-14, on the other hand, show that one can expect only two or three dB gain from orbit diversity.

### 7.4.3 Signal Diversity

Rain attenuation is not only spatially sensitive, as discussed earlier, but also time and frequency sensitive. This property provides an opportunity to combat rain fades by adjusting certain signal parameters in accordance with existing propagation conditions.

Suppose, for example, that the ground terminal continually adjusts its uplink power to maintain a constant signal level at the satellite, regardless of propagation conditions. Then rain fade mitigation is achieved without a need for redundant signal paths. In a similar way, the satellite can use transmitter power control to mitigate downlink rain fades.

Alternatives to transmitter power control for combatting the time dependence of rain fades in digital communication systems are to use either forward error correction (FEC) or data rate control. Rather than raising the transmitter power when propagation conditions worsen, one can temporarily apply FEC to improve the power margin at the expense of a wider signalling bandwidth or longer transmission time. However in some situations, both power and bandwidth in the digital communication system may be limited. If this is the case, one can always temporarily lower the data rate to improve the power margin - the price being a slower communication rate.

The natural way to exploit the frequency dependence of rain attenuation is to use frequency diversity. When rain attenuation rises to some specified value, high priority traffic can be diverted to a lower frequency that is less susceptible to rain fades. The price paid in this case is a reduction in channel capacity during rain fades, and the requirement for additional frequency assignments.

All of these techniques for incorporating signal diversity in satellite communication are discussed in the following paragraphs.

#### 7.4.3.1 Power Control

The objective of power control is to vary the transmitted power in direct proportion to the attenuation on the link, so that the received power stays constant through rain fades. This can be employed, in principle, on either the uplink or downlink. There are two reasons for using power control rather than a very high transmitted power level to mitigate rain fades. When used on the uplink, the reason is usually to prevent the transponder on the satellite from being overdriven, or to keep from upsetting the power balance among several uplink carriers using the same transponder. (When multiple carriers share a non-linear transponder near saturation, variations in the input level of one of them are enhanced at the output.) When used on the downlink, the reason is